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## 2.5 dimensional model of mantle heterogeneities under the Ukrainian shield according to the gradients of the velocities of seismic waves

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**Abstract.** We analyze the basic techniques for the investigation of the deep structure of the mantle and the shortcomings of the models of mantle structures derived from them. Thus, we reveal that there is no analysis of the velocity field by means of analytical transformants.

Therefore, we developed and tested a new approach to define the mantle boundaries based on the calculations of the sequence of  $P$ -waves velocity derivatives. As a result, we obtain some new set of velocity gradient distributions for the principal tectonic structures of the Ukrainian Shield along the composite profile. The boundaries of the mantle discontinuities according to the velocity gradient we define in a special manner to eliminate the false anomalies and the fluctuations of the velocity curves that occur due to the conversion of the hodograph into the mean velocities. The smoothing of the velocity curve we perform with a previously defined wavelength step being equal to 50 km. We treat the calculated velocity gradient anomalies as the useful signal response above the appropriate sections, which have different velocity accelerations levels inside the upper mantle. We assume that the mantle anomalies have the same physical background (density/viscosity distributions, temperature gradients etc.) within each range with the equal acceleration value. However, the singular points determined by the inflections of the gradient curve could be the possible boundaries of additional inhomogeneities within the mantle. We calculate both the 1<sup>st</sup> and the 2<sup>nd</sup> derivatives for the velocity curves obtained. The excesses 2.5-D model of the 1-th and 2-th gradient curves (the acceleration of the  $\text{grad}_p$  itself) determine the position of the max / min anomalies of  $\text{grad}_p$  at the consolidated seismic profile within the Ukrainian Shield. Finally, we analyze in detail the distribution of velocity gradients of  $P$ -waves within the upper mantle in the depth range of 50–750 km. It results in the identification of a series of additional gradient velocity boundaries within three principal structural horizons of the upper mantle (under ~ 200–300 km, ~ 410–500 km, and ~ 600–650 km respectively).

**Keywords:** mantle discontinuities, 2.5D model, directional derivatives, velocity inversion, gradient analysis, mosaic pattern, depth correction, tectonic structures, gradient-like change, seismic  $P$ -waves, curve inflection, Ukrainian Shield

## 2.5-вимірний модель мантійних неоднорідностей під Українським щитом за даними градієнтів швидкостей сейсмічних хвиль

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**Анотація.** Проаналізовано основні методи вивчення глибинної будови мантії та недоліки отриманих за їх допомогою моделей мантійних структур. Виявлено, що відсутній аналіз поля швидкості за допомогою аналітичних трансформант. Випробувано новий підхід до визначення меж мантії, заснований на розрахунках послідовності похідних швидкості  $P$ -хвиль. Отримано 2.5-D модель розподілу першого та другого градієнтів швидкості для основних тектонічних структур Українського щита вздовж зведеного профілю. Межі мантійних неоднорідностей за даними градієнта швидкості визначені таким чином, щоб усунути помилкові аномалії і коливання швидкісних кривих, що виникають при перетворенні годографа у середні швидкості. Згладжування кривої швидкості проводилося із визначеним наперед кроком довжини хвилі, що дорівнює 50 км. Обчислені аномалії градієнта швидкості трактується як відгуки корисного сигналу над ділянками, що мають різні рівні прискорення швидкості у верхній мантії. У межах кожного інтервалу з однаковим значенням прискорення ми припускаємо наявність аномалій речовини мантії однакової природи (розподіл густини / в'язкості, градієнти температури і т.п.). Проте особливої точки, які визначаються за перегибами градієнтної кривої, є можливими межами додаткових неоднорідностей у мантії. Ми обчислили як першу так і другу похідні для отриманих кривих швидкості. Перевищення градієнтної кривої (а саме прискорення  $\text{grad}_p$ ) визначають положення максимуму/мінімуму аномалій  $\text{grad}_p$  із зведеного сейсмічного профілю на Українському щиті. Проведено детальний аналіз розподілу градієнтів швидкості  $P$ -хвиль у верхній мантії для глибин 50-750 км. Виявлено ряд до-

даткових градієнтних швидкісних меж в рамках трьох основних структурних горизонтів верхньої мантії (до ~ 200-300 км, ~ 410-500 км і ~ 600-650 км відповідно).

*Ключові слова:* мантіїні межі, 2,5D модель, похідні за напрямом, інверсія швидкості, градієнтний аналіз, мозаїчна схема, поправка за глибину, тектонічна структура, градієнтні зміни, сейсмічні Р-хвилі, вигин кривої, Український щит

**Introduction.** The question of the internal structure and tectonic evolution of Earth are a fundamental task for geophysics in general and seismology in particular. The search for the answers appears to be possible after obtaining the geophysical models with a detailed description of various physical properties of the Earth's crust and a mantle. For the crust itself, the construction of such models is most often associated with the various techniques of seismic inversion. For the most part, the solutions of these problems are based on the data of deep seismic sounding (DSS) methods, when studying the *velocity parameters* of the Earth's crust, or the common deep point (CDP) when determining the *sharp changes* in the physical properties of the Earth's crust or reflecting boundaries.

In addition to seismometry, since the 1980s many researchers have started to actively use the methods of magnetotelluric sounding (MTS) and magnetovariational profiling (MVP) to study the deep structure of the lithosphere. These two approaches allowed them to explore the heterogeneity of the distribution of the geoelectric properties of the geological medium (the effective resistance and the conductivity). A comprehensive solution of the inverse problems of geophysics, using the data from the DSS / CDP and MTS / MVP, as well as 3D modelling of gravity and magnetic fields is based on the above-mentioned seismic and electromagnetic studies. It allows one to obtain the additional information about the structure of the Earth's crust and the upper mantle and the features of deep tectonics (Pigulevsky, 2011).

In addition to seismic methods, for the construction of a physical and mathematical model of the internal structure of the crust and the upper mantle of the Earth, the solutions of direct and inverse problems of gravity and magnetic prospecting derived from the data of relevant measurements are widely used (Kupriyenko et al., 2007). Based on the complex of the established physical parameters of the geological medium (such as velocity, density, magnetic susceptibility, etc.), one can form the basis for the transition to a general physicochemical model of the medium.

To study the mantle as a whole, the possibilities of gravity and magnetic methods are restricted by the degree of stability of the recalculation of potential fields only to certain depths. Another limitation is the loss of the magnetic properties due to the increase of the mantle temperature with a depth reaching the

Curie point where the rock magnetic properties disappear. Therefore, to obtain the correct physical and chemical models of the mantle, researchers are left with only seismological and, to a lesser extent, deep electrometry methods.

**A review of methods for studying the mantle.** The modern seismology methods that map the mantle inhomogeneities according to changes in the seismic wave velocity are a combination of traditional high-resolution tomography methods and seismological methods that analyse the reflection or scattering of the acoustic waves at the boundaries with sharp changes in the seismic properties of the mantle. One of these methods, for example, is a combination of long-period normal seismic modes and the surface waves with the observations of bulk waves with the shorter periods (Lawrence and Shearer, 2006).

The boundaries obtained by seismological methods (the intervals of a sharp change in the seismic properties of the mantle) can significantly supplement the information collected by seismic tomography methods. With the help of these, it is possible to receive only a bare image of the structural levels of the mantle. The sharp discontinuities within the mantle can be detected using the seismic bulk waves that are reflected, transformed, or refracted at these boundaries. To map the mantle boundaries, various combinations of scattered and reflected waves are used: *S-P* scattering; *P-P* scattering in front of the *PP* waves; *P-P* scattering before *P*-waves, and *P-P* scattering before *PKP* ones (Kaneshima, 2016; Jenkins et al., 2017).

Other tomographic studies, which additionally take into account the effect of temperature on changes in velocity within the studied area, helped to identify the changes in the chemical composition and phase transitions in the lower mantle. Applying these methods, some geodynamic features were revealed, such as the *sinking lithospheric plates*, the *ascending plumes* (Trampert and Fichtner, 2013). Over the past decades, global seismology has achieved a significant success in mapping the deep heterogeneities of the mantle.

So far, numerous attempts to establish a correlation between seismic inhomogeneities of the mantle and the main mineral and phase transitions, as well as the spin transition, are associated with numerous difficulties (Irifune et al., 2010). Given this, the main assumptions about the origin of mantle inhomogeneities

are associated generally with the local and regional chemical anomalies within the mantle (Liu, 1974). Also, a series of chemical anomalies and phase transitions in the upper and lower mantle have been identified (Deuss et al. 2013; Trampert and Fichtner, 2013; Muirhead and Hales, 1980; Petersen et al., 1993).

The development of the seismological methods that allow data to be obtained on the inhomogeneities in the mantle has been laid down since the 1970s when the generalised 1-D velocity models were obtained (Johnson, 1969; Dziewonski and Anderson, 1981; Kennett et al., 1995). In 1969, Johnson (Johnson, 1969) identified the main mantle zones using a gradient analysis of a 1-D velocity curve. With the further development of the seismological methods, this approach has been forgotten for a long time. We show in this article that the application of the *P*-wave velocity gradient analysis can successfully produce new data on the allocation of mantle heterogeneities.

In our opinion, one of the reasons that hinder the complete extraction of useful information from the available data on the seismic velocities mapping is the lack of the researches that use various linear transformants from the source traveltimes data. At the same time, their application in the potential fields (most often in gravity and magnetic exploration) allows construction of the new models of the geological medium, and obtaining new information about its structure. Thus, for example, gravity tomography is used for bulk density modelling of the complex geological structures where density varies with the depth ambiguously. The approach performs an iterative procedure of averaging the observed gravity field  $\Delta g_{\text{obs}}$  by the multiple bandpass filtering with a gradual decrease in filter parameters towards to lower frequencies. But the possibilities of filtration in assessing the depth  $h$  of anomalous bodies are restricted by the dependence of the spectral characteristics of the observed gravity field  $\Delta g_{\text{obs}}$  on the depth  $h$  and the geometry ( $a$ ,  $b$ ) of the sources of the anomalies, as well as the low resolution (accuracy) of the reconstruction of studied structures.

The application of the ideas of the gravity tomography can also be useful for processing the data from the seismic tomography. In particular, as transformants for the velocity field, one can propose the calculation of their gradients for the specific horizons (lateral layers) in the mantle. Indeed, in general, a gradient analysis of the *P*-wave velocity field represents simply some *gauge transformation* (for example, gravity and its potential).

Because of this, in our study, we propose to use an analysis of the behaviour of the gradients of 1-D

velocity curves, which show the peculiarities of the velocity change with depth. We define the inflections of the velocity curves as boundaries of mantle inhomogeneities, similarly to the approach used in (Johnson, 1969). Based on the preceding, the main goal of the paper is to study the inhomogeneities of the upper mantle within the Ukrainian Shield in the depth range from 50 to 750 km, according to the data of previously calculated *P*-wave velocity gradients.

**Modern ideas about the mantle structure.** The number of observed heterogeneities indicates a significant stratification of the mantle, in which three principal zones can be allocated. The upper mantle (up to 660 km) is the most heterogeneous part of it, and includes most studied discontinuities: the Mohorovičić boundary, the base of the lithosphere, discontinuities at the depths of 420 km and 660 km. The middle mantle includes a zone from 660 km down to 1300 km, which has heterogeneities under the subduction zones and tectonic plates, and a zone extending from 1300 km down to 1900 km, in which the inhomogeneities are mostly observed near the subduction zones. The lower mantle is a zone extending from 1900 down to 2700 km (to the boundaries of known layer D»), and it includes a small number of large inhomogeneities (Simmons et al., 2010).

The following boundaries are distinguished in the upper mantle.

The **Lehman boundary** (220 km) was for the first time discovered in North America (Lehmann, 1961). The PREM model (Dziewonski and Anderson, 1981) contains a strong heterogeneity at a depth of 220 km. The presence of this boundary in the PREM model suggests that it represents a global discontinuity. However, it is not *clearly* defined on the global scale and does not have clear *precursors* of *SS* waves; precursors of *PP* waves have regionally linked *phases*. Therefore, this boundary has a regional significance. This boundary is associated not with an *increase* in the *melt fraction* in the mantle but with the *physical structure* of the mantle which signifies a change from *anisotropic* structure above to isotropic one below.

The **X-boundary** (350 km) was revealed (Revenaugh and Jordan, 1991) at a depth of 300–360 km as a discontinuity in *ScS* reverberations. Revenaugh and Williams (2000) primarily find an X-discontinuity in areas of active or ancient subduction under the continental crust. It could arise due to phase transitions.

The **410 km boundary** is characteristic of 1-D Earth reference models such as PREM (Dziewonski and Anderson, 1981). It is identified in all regions where there are enough data and can be consistently seen in the precursor waves *SS* and *PP*. This discon-



tinuity is observed through other datasets, including the global studies of reception functions (Chevrot et al., 1999; Lawrence and Shearer, 2006; Andrews and Deuss, 2008), and *ScS* reverberation (Revenaugh and Jordan, 1991). It could be due to the partial rock melting, presence of water or other *chemical heterogeneities* in the transition zone.

The **520 km boundary** was for the first time discovered using *SS* precursor waves (Shearer, 1990, 1991). Using synthetic seismograms with velocity gradients in the transition zone, Bock (1994) revealed that due to phase transitions this boundary can be seen in seismograms for models without a 520 km boundary. Most of the modern studies of *SS* precursors indicate that they are related to this boundary. It occurs only in certain regions, mainly the oceans.

The **660 km boundary** has been known for a long time, but its nature is still debated. There is a hypothesis that the physical properties of minerals (the transition from ringwoodite to perovskite and magnesio-wüstite) predict the opposite behavior of the topography of the 660 km discontinuity compared to that of the 410 km: it deepens in the cold regions of the mantle and rises within hot regions. These predictions have been compared to the tomographic velocities. In contrast to the 410 km boundary, the tomography of the 660 km boundary correlates with tomographic shear wave velocities (Flanagan and Shearer, 1998; Houser et al., 2008) and is depressed in the subduction zones.

**The approach to the analysis of velocity curves.** The method of the gradient analysis of velocity curves arose in the 1970s from the method of interpretation of 1-D velocity models when the main mantle zones were identified. The first study was conducted by Johnson (1969) in the late 1960s, while examining 212 deep earthquakes. He revealed the global anomalies of  $v_p$  gradients at the depths of 830, 1230, 1540, 1910 and 2370 km and suggested that these anomalies could be caused by changes in the composition and density of the mantle.

The method for the gradient analysis of curves itself is well known from the mathematical function analysis and it is widely used in both geophysics and other disciplines. Let's recall the theoretical foundations of the gradient analysis (Fichtenholtz, 1964), determining its analytical content.

The mathematical meaning of the gradient is based on the fact that the gradient is a result of differentiation of the complex function  $v$  in the direction  $\vec{e} = (e_1, \dots, e_n)$  of the elementary vector basis:  $\partial v / \partial \vec{e} = \partial v / \partial x_1 \cdot e_1 + \dots + \partial v / \partial x_n \cdot e_n = (\nabla v, \vec{e})$ . To calculate the directional derivative, it is sufficient to know the gradient of the function (a set of partial derivatives).

The gradient  $\nabla = \partial / \partial x \cdot \vec{e}_x + \partial / \partial y \cdot \vec{e}_y + \partial / \partial z \cdot \vec{e}_z$  of the scalar function (such as the potential, the strength, the tension)  $v(x)$  is the vector  $\nabla v(x)$ , whose components are the partial derivatives (projections on the appropriate coordinate axis) of the scalar function  $v(x_i)$ . It describes the scalar field of the given function  $v(x_i)$  through its directional derivative. Determining at each point of the functional space  $R^{(3)}$  the routine direction and the rate of the maximum change in the scalar field, the gradient sets the measure of change within the certain functional space of this scalar field per unit of length.

The geometric meaning of the gradient coincides with the directional derivative, as the projection (a scalar product) of the gradient vector onto the direction vector

$$\frac{\partial v}{\partial l} = (l, \text{grad} v); \text{ if it is true } l \cdot |\text{grad} v| = \text{grad} v,$$

then it follows

$$\frac{\partial v}{\partial l} = (l, \text{grad} Q) = |\text{grad} v|.$$

That is, it is a measure of the *slope* of the tangent plane to the surface of the function at a given point (Kudryavtsev, 1981). If a surface is given by a regular equation, its gradient is a **vector** in a tangent plane passing through a *given point* on the surface and directed toward the surface *maximum*. For a surface broken by level lines (the intersection of planes being perpendicular to the axis of  $v(x_i)$  with this surface), the gradient is simply the perpendicular to the level contour passing through this point. Numerically,  $\text{grad} v(x)$  equals to the surface *growth rate* (in units of measurement) in the direction of the gradient and is expressed by the *maximum value* of all *directional derivatives*.

The last property of the gradient is the most useful for the analysis of the boundary features of the above mentioned *P*-wave velocity curves. We will use it as a criterion for distinguishing the boundaries of sections of an abnormal change in seismic wave velocity by the values of the maximum of its gradient along a linear profile. We use this comprehensive and straightforward analysis tool to map the mantle discontinuities that are identified on the interface within the mantle by the kinks of *P*-velocity curves. These curves constitute the mantle velocity model beneath of the Ukrainian Shield.

**Raw data and their preprocessing.** As the initial data, we used the 3D *P*-velocity model of the mantle beneath the Ukrainian Shield, presented in papers (Geyko, Shumlianska et al., 2006; Shumlianska et

al., 2014). This model was built using the Taylor approximation calculation technique for seismic tomography, developed by V.S. Geyko in the Institute of Geophysics of the National Academy of Sciences of Ukraine (Geyko, 2004). It represents a set of 1-D velocity curves, obtained by the hodograph reversal. The combination of these curves makes up a kind of quasi-3-D model of the studied geological medium.

To construct the hodographs using the Taylor approximation technique, we used the initial data on the times of the first *P*-wave arrivals from earthquakes with magnitudes  $M \geq 4.5$ . The data on the first arrivals of *P*-waves were taken from the seismological bulletins of the International Seismological Center, ISC (<http://www.isc.ac.uk/>) since 1970. One-dimensional hodographs are formed for the selected region by sampling the values of time-to-the-distance from the common time arrivals field. The last is presented in the format of a midpoint over a given rectangular area, covering each individual tectonic structure of the Ukrainian Shield.

The collected hodographs were subjected to an inversion procedure to convert them into velocity curves  $v_p$ . For the mantle beneath the Ukrainian Shield, two modifications of the seismic-tomographic model were obtained. In the first model (Geyko, Shumlianska, 2006), the fixed velocities in the crust were received from the Jeffreys-Bullen model (Dziewonski, Anderson, 1981). For the second seismic-tomographic model (Shumlianska et al., 2014), the velocities are taken from the average velocity model for the crust, calculated according to the data from the DSS carried out in 1960–80s (Tripolsky, Kaluzhnaya, 2001).

The set of velocity curves (quasi-3D model) is such that each velocity curve characterises some volume of the geological medium, assigning velocity values  $v_p$  to each point inside this volume. The 1-D velocity curves that constitute the seismic tomographic model of the mantle of the Ukrainian Shield are obtained by the inversion of seismic hodographs of refracted *P*-waves. That imposes certain restrictions on the obtained velocity solutions. Indeed, all the existing methods of solving of the inverse kinematic seismic tasks, including the Taylor approximation approach, are based on conceptions of a geometric seismic (Artemiev, 2012).

Under its provisions, the conditions for applicability of seismic methods and their resolution range are defined by the strict limitations that *elastic media* must satisfy. First, this is the ratio of the perturbation wavelength to the *characteristic dimensions* of the medium inhomogeneities under the study. Consideration of sufficient conditions is carried out based on

ideas about Fresnel volumes. These conditions are as follows: the parameters of the geological medium, as well as the parameters of the wave (the amplitude and the phase gradient) should not *noticeably change* in the cross-section of the Fresnel volume. It means that the minimum size of the distinguished features of media *cannot be less than the Fresnel volume* (Kravtsov and Orlov, 1980). Therefore, based on this principle restriction we selected the initial approaches for primary processing materials.

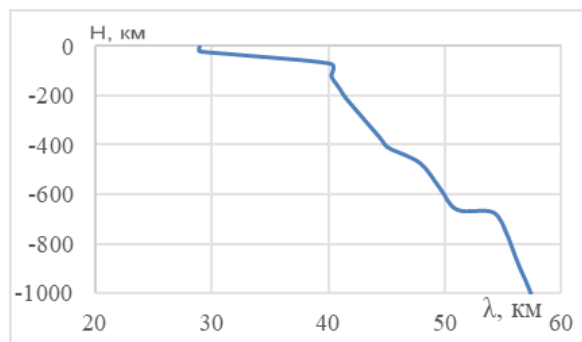
For most earthquakes, the periods  $T_p$  of longitudinal waves are within the range of 5–10 s (Savarenskiy, 1952). The approximate perturbation wavelength  $\lambda$  is calculated as  $\lambda = v \cdot T_p$ , where  $v$  is the wave velocity,  $T_p$  is the wave period. Its graph depending on the depth in the mantle beneath the Earth's surface is shown in Fig. 1 for the IASP91 velocity model (Kennett et al., 1995).

Keeping this in mind, we will consider the problem of the determination of the boundaries of the mantle discontinuities by the anomalies of the gradient  $v_p$  of the velocity curve. The first stage of such an analysis consists in the elimination of the possible artificial anomalies and fluctuations in the velocity curve that occurred due to the iteration of the algorithm of numerical inversion of the hodograph into the velocity curve. We call this procedure the smoothing of the *several* curve with a step that commensurates the wavelength  $\lambda$ . It equals to 50 km for a depth range of 200–700 km and 30 km for a depth range of 0–200 km (within the lithosphere).

As can be seen from Fig. 1, at depths of 0–700 km, the wavelength ranges from 30 to 50 km. This gives us a rough estimate of the resolution of the ray-tracing approach of seismic tomography, including the Taylor approximation.

Thus, at the first stage, before the analyses of the curvature of the velocity curves by the values of their gradients, the smoothing by the corresponding wavelengths is performed. The boundaries of mantle discontinuities are determined by the extrema of the first level gradient (Fig. 2). Studying the anomalies of the *gradient* of the  $v_p$  curve, we identify the areas with the different velocity *acceleration* of seismic *P*-waves (in accordance with the physical meaning of the gradient) at the certain sections of the whole upper mantle within 0–700 km.

Within each interval with the same velocity acceleration value, we assume the presence of anomalies of the mantle substance (the disturbing layer of a certain thickness) of supposedly the same physical background. The inflection points of the second level gradient  $v_p$ , which we determine by the extrema of

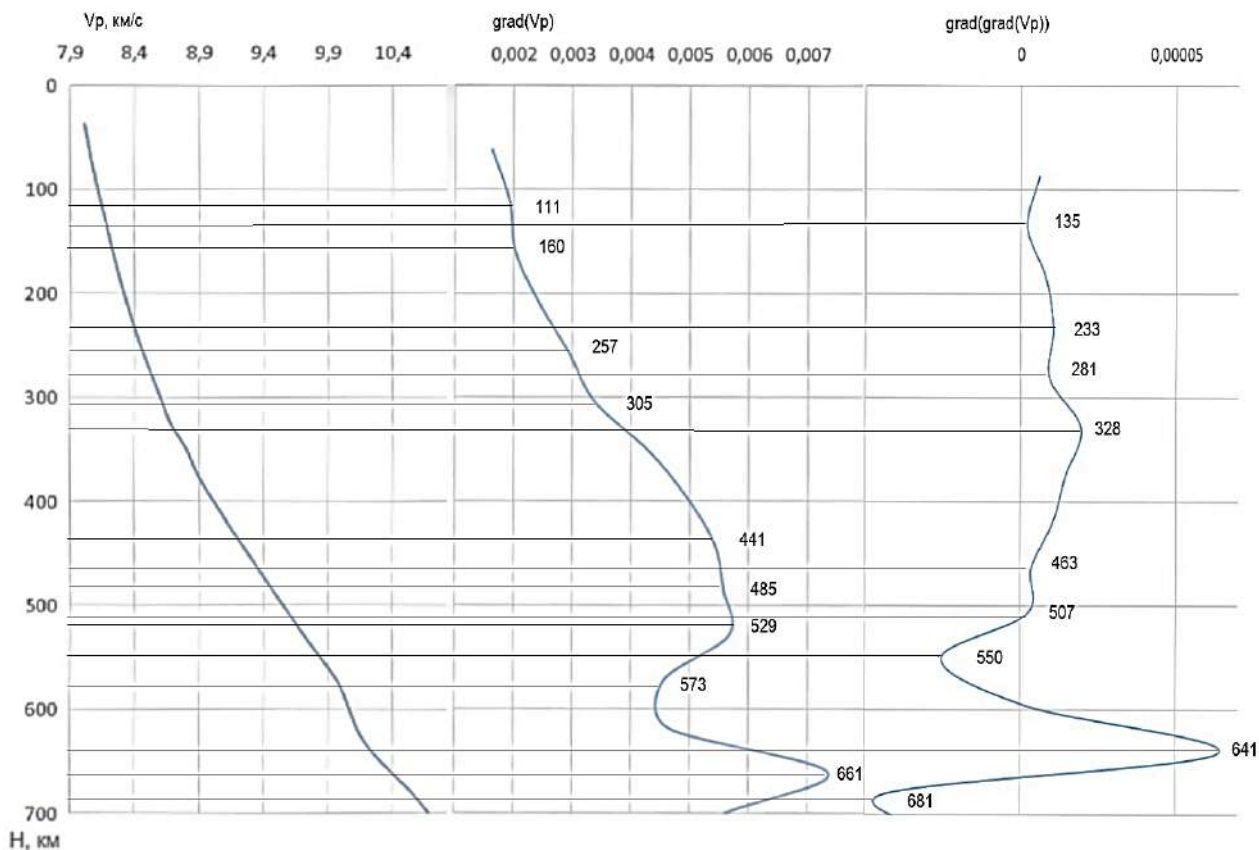


**Fig. 1.** Wavelength graph for earthquakes with a longitudinal wave period of 5 sec shows the velocity distribution for depth range 0–1000 km given for the IASP91 model. This chart provides a rough estimate of the resolution both of the ray tracing for seismic tomography and the method of Taylor approximation

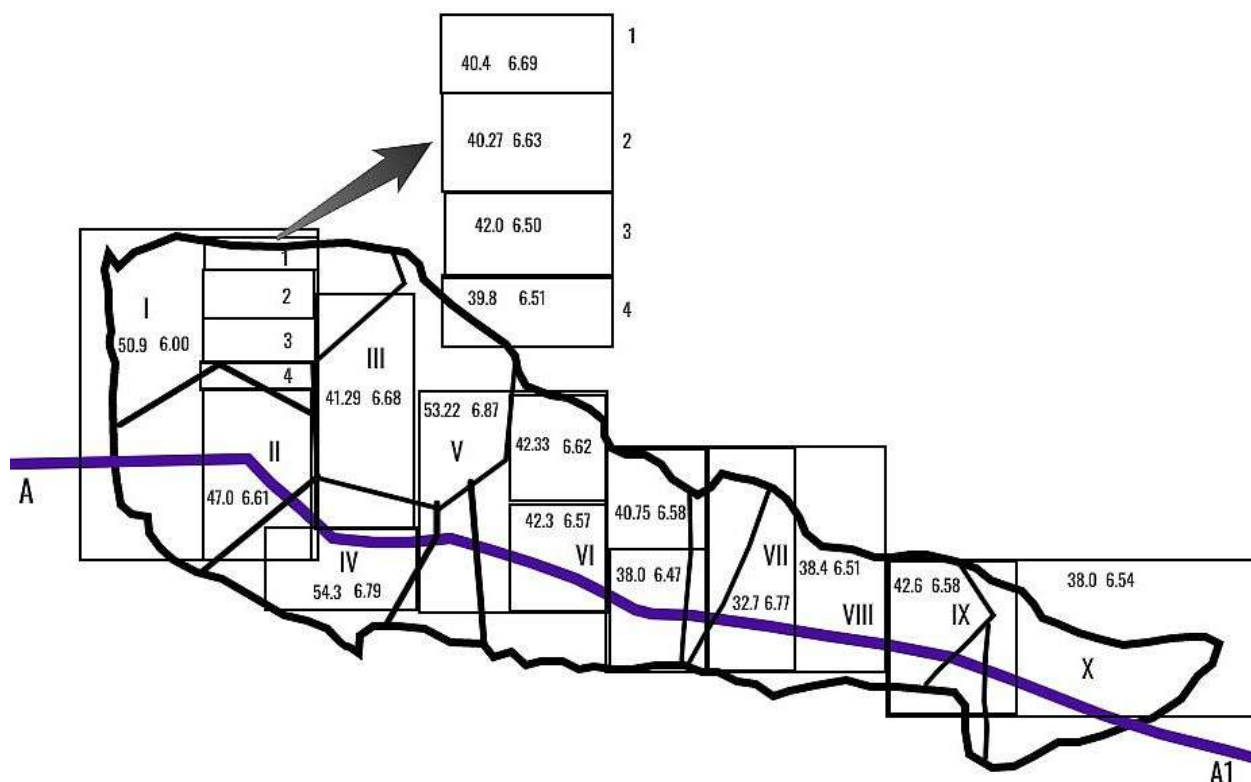
the gradient curve  $\text{grad}(\text{grad}v_p)$ , show the maximum and minimum points of that gradient curve  $\text{grad}v_p$ . It gives us valuable additional information about the local vertical and lateral variations of velocities in the mantle. The physical meaning of the second-level gradient can be interpreted as *zonal distribution* of the mantle anomalies, and the maximum and minimum points of the second gradient indicate the depth of the maximum and/or the minimum of the mantle anomalies that are established inside the mantle boundaries identified by the first gradient (Fig. 2).

**Results of the study.** Using the indicated technique, the velocity curves  $v_p$  and the velocity gradients were

calculated for the principal tectonic structures of the Ukrainian Shield along the composite profile A-A1 (Fig. 3). This profile crosses the Podillya and the Bug blocks, the Holovanivsk suture zone, the Inhul block, the Kryvyi-Rih-Kremenchuh suture zone, the Middle-Dnieper block, the Orikhovo-Pavlohrad suture zone and the Azov block. Each vertical column within the selected block is associated with geographical coordinates of the central point of the block (Fig. 4). Moreover, each selected block is represented by a 1-D velocity curve  $v_p$ . Each such curve was transformed for subsequent gradient analysis according to the described above procedure.



**Fig. 2.** Velocity curve  $v_p$  and its gradients, the anomalies of which determine the possible boundaries in the upper mantle under the Azov block of the Ukrainian Shield



**Fig. 3.** The layout of the profile A-A1 along the principal tectonic structures of the Ukrainian Shield. The division of structures and a description of their velocity characteristics are detailed in (Shumlianska et al., 2014). The average Earth core model of the Ukrainian Shield with the Moho depths (in km) and the mean velocities (km/s) within the Moho discontinuity. The tectonic structures are numbered as follows: I – Volynskiy megablock, II – Podilskiy megablock, III – Rosynskiy megablock, IV – Bugskiy megablock, V – Golovanivska suture zone, VI – Inguletskyi megablock, VII – Kryvyy-Rih-Kremenchug suture zone, VIII – Middle-Dnieper megablock, IX – Orikhovo-Pavlogradska suture zone, X – Priazovskiy megablock.

The boundaries of the blocks (Fig. 3) are defined in course of the analysis of the average velocity field which was collected from the DSS (deep seismic sounding) data (Shumlianska et al., 2007; Shumlianska et al., 2014).

The lines of the delimitation of the red and blue areas determine the position of the extrema of the  $\text{grad}_p$  anomalies down to a depth of 700 km. The maximum and minimum of the extreme points of the second level gradient of the velocity curves are shown in red and blue, respectively. Detailed analysis of the mantle gradient velocity pattern revealed several features. For instance, a wide zone of lowered values of the second level velocity gradient  $\text{grad}(\text{grad}_p)$  extends from the the Holovanivsk suture zone to the Orikhovo-Pavlohrad suture zone down to a depth of 100 km.

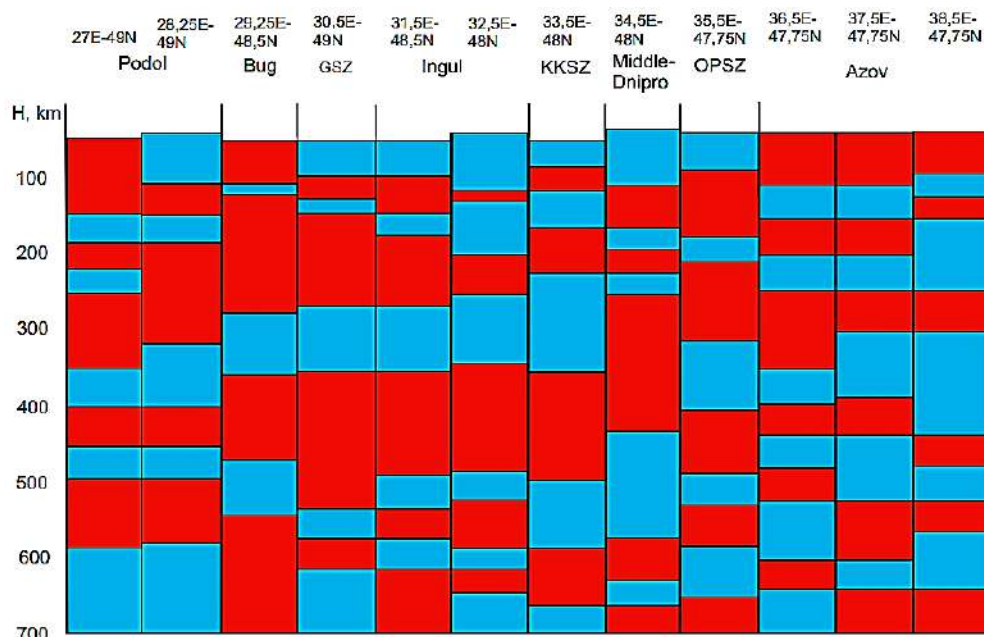
The Podillya block is clearly divided into western and eastern geostructural parts, and Azov block is divided into three similar parts. All of the suture zones are characterized by a mosaic (keyboard-like) alternation of the layers with maximum and minimum values of the second level velocity gradient  $\text{grad}(\text{grad}_p)$  within the upper mantle. The common disposition of the boundaries of the high velocity

“levels” does not deviate significantly from the known velocity models of the mantle beneath the Ukrainian Shield in the lateral direction, but the depth varies considerably. So, which known model of the mantle can serve as the reference model? An explanation of the localisation of the structural and the prediction of the material composition of the mantle require a further study.

A qualitative analysis of the calculated velocity transformations (Fig. 4) for the upper part of the upper mantle section down to a depth of 200 km has shown some similarity between the obtained model of the upper mantle and the model earlier proposed by O. Gintov and I. Pashkevich. In particular, the depth of the lithosphere base obtained by Gintov and Pashkevich (2010) in the Inhul and Middle-Dnieper blocks, according to thermal data (200–220 km), coincides with the depth of the first, starting from the crust, boundary according to the first velocity gradient. It is painted in blue (the  $\text{grad}_p$  minimum) in concordance with the value of the second level velocity gradient (Fig. 4).

At the same time, according to the previous lithosphere model (Gintov and Pashkevich, 2010), the base of the lithosphere in the eastern part of the





**Fig. 4.** The distribution pattern of mantle discontinuities along the A–A1 profile obtained from the first derivatives of the velocity gradients  $v_p$  of P waves (boundaries of the inhomogeneities); red and blue colour indicate the maximum and minimum value of the gradient of the second level  $\text{grad}(\text{grad} v_p)$ , respectively. The literal indices for tectonic units above the graph are as follows: Podil stands for the Podillya block; Bug is for the Bug block; HSZ is for the Holovanivsk suture zone; Inghul is for the Inghul block; KKSZ is for the Kryvyi-Rih-Kremenchuh suture zone; Middle-Dnieper is for the Middle-Dnieper block; OPSZ is for the Orikhovo-Pavlohrad suture zone and Azov is for the Azov block (after Pigulevskiy et al., 2019)

Ukrainian Shield (Azov block) rises relative to the central part of the shield up to the depth of 160–180 km. In our model there is no layer with maximum values of the acceleration of the velocity gradient (the second level velocity gradient), and this area is shown in blue colour.

Thus, two independently obtained models resulted in the qualitatively *comparable* picture with a deflection of the lithospheric layer in the central part of the Ukrainian Shield. In our opinion, it additionally testifies the physically determined reasons for the existence of the gradient boundaries which we obtained in the principal tectonic structures of the Ukrainian Shield.

During consideration of the velocity distribution patterns, it is necessary to pay special attention to the following features.

#### **Analysis of the mantle velocity gradient anomalies.**

A qualitative study of the graphic visualisation of the seismic *P*-waves velocity gradients vertical distribution in the upper mantle beneath the principal tectonic structures of the Ukrainian Shield revealed the following clear image. According to the preliminary qualitative interpretation of the field of the first and second gradients (the velocity derivatives), at least 4 “refracting horizons” (by the inflections of the first gradient) were identified at the depths of 200–220 km, 400–410 km, 510–525 km and 640–660 km. Moreover, these narrow horizons generally coincide with the

critical intervals at which the mantle transition zones are distinguished (Deuss, 2009). Taken together, the obtained boundaries are combined into layers characterising the lithospheric and asthenospheric layers in general, with the depths inherent to the mantle under the continental platforms (Gavrilov, 2005). The layers generally corresponding to the commonly recognized division of the upper mantle are also allocated below these conditional boundaries.

However, the extent and horizontal localization of zones along the studied profile A–A1 is noticeably variable (Fig. 3). In particular, according to the field of the *P*-wave velocities first gradients, the following areas were distinguished:

Three sections of the velocity gradient boundary transitions in the depth range of 200–220 km: from 31 E, 49 N to 32 E, 48.5 N there is the transition from the Holovanivsk suture zone to the Inghul block; from 33 E, 48 N to 34 E, 48.5 N there is the transition from the Inghul block to the Kryvyi-Rih-Kremenchuh suture zone; from 36.5 E, 47.75 N to 39 E, 47.75 N there is the Azov block;

One section occurs in the depth range of 400–410 km (from 29.5 E, 48.5 N to 32 E, 48.5 N, a transition between the centres of the Bug and Inghul blocks);

Two sections are located in the depth range of 510–525 km (from 33 E, 48 N to 34 E, 48.5 N, a transition from the Inghul block to the Kryvyi-Rih-Kremenchuh suture zone; and from 35 E, 48 N to



38.75 E, 47.75 N, a transition between the centres of the Middle-Dnieper and Azov blocks).

At the same time, according to the field of the second derivatives for the  $P$ -wave velocities, the following stand out:

Two sections of the boundary transitions of the velocity gradient in the depth range of 200–220 km: from 30 E, 48.5 N to 32 E, 48.5 N, from the centre of the Bug block to the western part of Inhul block; and from 36.2 E, 47.75 N to 38 E, 47.75 N, in the western part of the Azov block;

Four sections located within the depths range of 400–410 km: from 27 E, 47 N to 29.25 E, 49 N in the Podillya block; from 32.5 E, 48 N to 34.6 E, 48 N, in the eastern part of the Inhul block and the entire Kryvyi-Rih-Kremenchuh suture zone; from 36 E, 47.75 N to 37 E, 47.75 N in the transition zone between the Orikhovo-Pavlohrad suture zone and the Azov block; and from 38 E, 47.75 N to 39.5 E, 47.75 N in the eastern part of the Azov block;

Two sections occur in the depths range of 510–525 km: from 26.5 E, 49 N to 31 E, 48.5 N in the Podillya and Bug blocks and in the western part of the Holovanivsk suture zone; from 34.1 E, 48 N to 39 E, 47.75 N, from the centre of the Kryvyi-Rih-Kremenchuh suture zone to the eastern edge of the Azov block.

Both velocity derivatives unambiguously determine a thick transition zone of the medium physical properties according to the data of the  $P$ -waves velocity gradients in the depth range of 640–660 km. The horizontal boundaries of the transitional zone practically coincide and extend beneath the most part of the Ukrainian Shield from 32 E, 48.5 N, the western part of the Inhul block to 39 E, 47.75 N, the eastern edge of the Azov block).

Each of the selected finite sections (zones) implies a *sharp* (gradient-like) change in the velocity properties of the upper mantle, caused by a corresponding *proportional* change in its physical properties such as rheology, density, permeability, phase state, etc. We assume that the material of the upper mantle forms a *continuous* solid medium (layer) within the general seismic discontinuities, with the same physical properties. Therefore, in the subsequent interpretation, we will focus on the *effective density* of this medium, as a characteristic that is convenient to compare with the results of the analysis of data from other geophysical methods, and, in particular, the potential fields.

It should be noted that the mantle anomalies boundaries which we have identified generally correspond to the location of the known mantle

boundaries previously obtained using seismological and tomographic methods.

**Conclusions.** We analysed first and second gradients of 1-D velocity curves taken from the seismic tomographic  $P$ -velocity model of the mantle beneath the Ukrainian Shield. The obtained boundaries of mantle discontinuities fit the generally accepted division of the mantle proposed by other researchers. We received additional information on the distribution of the velocity curves concerning their second derivatives.

In particular, we collected the data set on the depth  $z_i$  of the allocation of the mantle discontinuities boundaries for the first derivatives (gradients) of velocity  $\text{grad}v_p$ , accompanied by the data set on the depths  $\zeta_i$  of distribution of the maximum and minimum of the second velocity gradient (derivative)  $\text{grad}(\text{grad}v_p)$ . These parameters, as well as their numerical values, allow us to conclude that we have obtained a combinatorial set (a set enclosed into a set) of the mantle velocity parameters beneath the Ukrainian Shield. Therefore, it meets the requirements to 2.5-D models (being the orthonormal projection of a 3D source in a 2D medium). Thus, the 2.5D model defines a series of isolated 2D objects and shows them at *different depths* and/or encodes different layers with various colours, as in our case (Fig. 4).

Thus, the obtained 2.5-D model of the velocity gradients (Pigulevskiy et al., 2019) complements the seismic  $P$ -velocity model of the upper mantle of the Ukrainian Shield (Shumlianska et al. 2014). The latter was produced taking into account corrections to the velocity model of the Earth's crust for the Ukrainian Shield, as well as the other well-known models (Pigulevskiy, 2011; Pigulevskiy, Svystun, 2014).

We distinguish the concepts of method accuracy and resolution. The resolution of the gradient analysis depends on the reference length of the seismic  $P$ -wave, which serves as an explicit criterion for the recognition of the Fresnel zone. The vertical accuracy of the velocity boundaries recognition in the upper mantle by inflections of the velocity curve gradient does not depend on the Fresnel zone, since we analyse a mathematically idealised velocity curve that is transformed (smoothed) taking into account the wavelength  $\lambda$ .

With this restriction, the boundaries identified by the extreme points of the gradients are uniquely determined. At the same time, the linking of each analysed velocity curve  $\text{grad}v_p$  to the middle point of the block with the established geographic coordinates allows us to obtain an accurate geographical lateral reference of the velocity boundaries of the blocks. Thus, the

accuracy of the determination of the lateral velocity boundaries along a composite profile depends only on the block size.

An exact geographical reference, in turn, allows one to obtain the *topology* of the mantle boundaries, and to link them for the first time to the location of the tectonic structures on the surface. Other methods considered in the above review, allow geo-referencing only at the regional scale. It is because most of the techniques that analyse seismograms for the presence of reflected phases or wave amplitudes do not imply any precise geographic location as these methods have a generalised character.

Further studies will be devoted to the analysis of the characteristic features of the spatial distribution of the discontinuities at the upper mantle and their possible physical background.

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